

All-Sky Earth Occultation Observations with the Fermi Gamma Ray Burst Monitor

Colleen A. Wilson-Hodge

NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

E Beklen

Middle East Technical University, 06531, Ankara, Turkey

P.N. Bhat, M.S. Briggs, V. Chaplin, V. Connaughton

University of Alabama in Huntsville, Huntsville, AL 35899, USA

A. Camero-Arranz

Fundacion Espanola de Ciencia y Tecnologia (MICINN), C/Rosario Pino 14-16, 28020, Madrid, Spain

G. Case, M. Cherry, J. Rodi

Louisiana State University, Baton Rouge, LA, USA

M.H. Finger

Universities Space Research Association, Huntsville, AL 35806, USA

P. Jenke

NASA Postdoctoral Program Fellow, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

R.H. Haynes

NASA Academy Program Fellow, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA

Using the Gamma Ray Burst Monitor (GBM) on-board Fermi, we are monitoring the hard X-ray/soft gamma ray sky using the Earth occultation technique. Each time a source in our catalog is occulted by (or exits occultation by) the Earth, we measure its flux using the change in count rates due to the occultation. Currently we are using CTIME data with 8 energy channels spanning 8 keV to 1 MeV for the GBM NaI detectors and spanning 150 keV to 40 MeV for the GBM BGO detectors. Our preliminary catalog consists of galactic X-ray binaries, the Crab Nebula, and active galactic nuclei. In addition, to Earth occultations, we have observed numerous occultations with Fermi's solar panels. We will present early results. Regularly updated results can be found on our website <http://gamma-ray.nsstc.nasa.gov/gbm/science/occultation>.

1. INTRODUCTION

1.1. Fermi Gamma Ray Burst Monitor

The Gamma Ray Burst Monitor (GBM) on board *Fermi* consists of twelve Sodium Iodide (NaI) detectors and two Bismuth Germanate (BGO) detectors, sensitive from about 8 keV to 1 MeV and 150 keV to 40 MeV, respectively. Continuous data from both detector types are received from GBM when the spacecraft is outside the South Atlantic Anomaly. They consist of two types, CTIME, with 256 ms nominal time resolution and eight energy channels, and CSPEC, with 4.096 s nominal time resolution and 128 energy channels [7]. For the NaI detectors the lower energy bounds of the 8 ctime bands are: 8, 12, 25, 50, 100, 300, 500, and 1000 keV. To date the Earth occultation technique has used only CTIME data, but future plans include applying the technique to CSPEC data as well.

1.2. Scientific Objectives

The goals of the GBM Earth Occultation Project are to:

- Search for rapid bright events such as AGN flares, rapid transients, black hole transient out-

burst onsets, and bright flares in known transient objects,

- Provide light curves and spectra of these events to the scientific community and to the LAT to allow correlations with LAT observations and the results of correlated multiwavelength observations,
- Monitor the majority of the soft gamma ray sky including known transient and variable objects such as galactic black hole transients, neutron star binaries, and AGNs, looking for long term changes and bright outbursts,
- Discover and study new transient objects and provide alerts to other instruments for more sensitive follow-up searches, and
- Reveal pre-discovery emission from sources that are newly discovered both by GLAST and by other observers.

2. EARTH OCCULTATION TECHNIQUE

The Earth occultation technique is currently used with GBM to monitor fluxes for a catalog of known sources. Sources are added to the catalog as they flare or upon request. For each source, the time of 50% atmospheric transmission at 100 keV is predicted using the known position of *Fermi*. A four-minute window of data is then selected centered on the predicted

time. NaI detectors are then selected if the angle between the detector normal and the source is less than 60° . The data in each energy channel for each detector are then fitted with a model consisting of a quadratic background and a scale factor times a model profile for each source. Model profiles for the source of interest and any other sources occulting within the fit window are computed by convolving the atmospheric transmission and detector response for each data point with an assumed energy spectrum for the source. The profile for each source is normalized using the count rate predicted by convolving the detector response at the occultation time with the assumed source spectrum (i.e., assuming no atmospheric transmission). Once scale factors are fitted for all detectors, a fit across detectors is then performed to find the best scale factor for all detectors. This scale factor is multiplied by the assumed flux model integrated across each energy channel to determine flux for each source.

This method differs considerably from the Earth occultation technique used with the Burst and Transient Source Experiment (BATSE) [3, 4] on the *Compton Gamma Ray Observatory (CGRO)*. *Fermi* is pointed $\pm 35 - 50^\circ$ from zenith, so the detector response relative to a particular source is constantly changing and must be accounted for within each individual step fit. *CGRO* remained at a fixed pointing relative to the sky for typically two-weeks, so the detector responses could be ignored for the individual step fits and needed to be applied only to compute fluxes. GBM has additional energy coverage in the 8-25 keV band, at lower energies than BATSE could detect. The placement of the GBM detectors on the spacecraft also results in occasional blockages by the solar panels and other parts of the spacecraft. These must be accounted for in the detector response as well. Currently the solar panels are not well modeled in the detector response because they are constantly moving. If a detector is blocked by a solar panel during a fit window, it is excluded from the fit.

3. SOURCE MONITORING RESULTS

As of December 15, 2009, we are currently monitoring a catalog of 64 sources (60 X-ray binaries, 3 AGN, and the Crab) with GBM Earth occultation. For 49 of these sources Earth occultation measurements have been made from August 12, 2008 until December 15, 2009, and preliminary analysis has been performed. Preliminary detections are listed in Table 1: Y denotes $> 10\sigma$ statistical significance for the mission long average in at least one energy channel (37 sources), T denotes transient activity consistent with Swift/BAT (5 sources). Sources added recently, with incomplete histories and analysis are listed in Table 2. Sources not currently marked as detections, especially transients, may be detectable with further

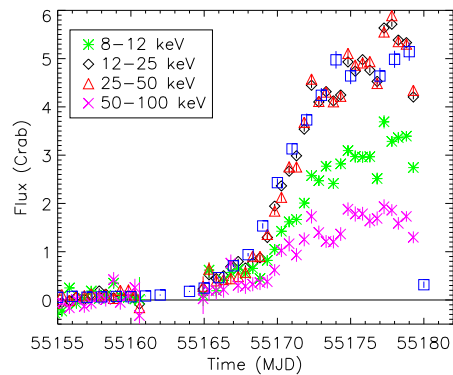


Figure 1: A 0535+262 giant outburst. Green asterisks, black diamonds, red triangles, and pink crosses denote 8-12, 12-25, 25-50, 50-100 keV GBM fluxes averaged over 1/2 day, respectively. Blue squares denote 1-day Swift/BAT 15-50 keV fluxes.

analysis. Consistency checks were performed by comparing GBM and Swift/BAT Hard X-ray Transient Monitor¹ measurements normalized the Crab. Light curves are shown for selected sources below. Systematic problems due to interfering sources are still present at times in the light curves. Optimizing the list of sources to be considered in step fitting is an iterative process and these effects will likely improve with future runs through the GBM data.

3.1. Recent Transients

A 0535+262, an 103-second accreting pulsar, began a giant outburst in late November 2009 [8]. The flux rose rapidly to nearly 6 Crab in the 12-25 keV and 25-50 keV bands and about 2 Crab in the 8-12 keV and 50-100 keV bands on December 10, 2009. The light curve of this outburst is shown in Figure 1. Interestingly, the 12-25 and 25-50 keV bands track each other closely and both agree well with Swift/BAT. The A0535 giant outburst is not detected in daily averages in the 100-300 keV band. Since *Fermi* was launched, A 0535+262 underwent four normal outbursts prior to the giant outburst. Figure 2 shows the comparison between GBM and Swift/BAT data for these outbursts. Pulsations from A0535+262 are detected with the GBM pulsar monitoring technique [5].

H1417-624 is Be/X-ray transient pulsar with a 17.5 s period [1] that began a giant outburst in late October 2009. GBM detects H1417-624 in the 12-25

¹<http://swift.gsfc.nasa.gov/docs/swift/results/transients>

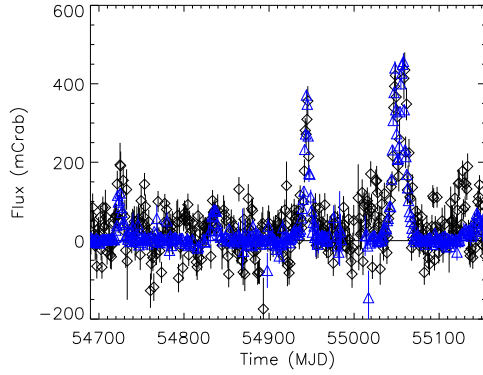


Figure 2: A 0535+262 normal outbursts observed with GBM. Black diamonds and blue squares denote GBM 12-50 keV and Swift/BAT 15-50 keV measurements, respectively.

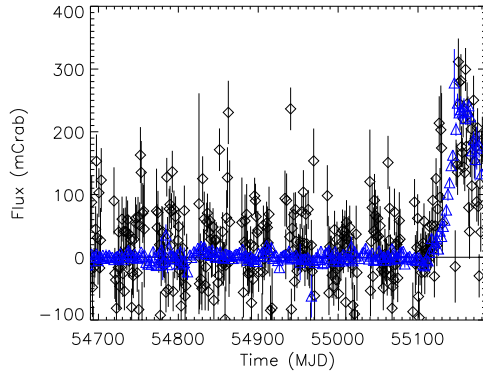


Figure 3: H1417-624 long-term flux history. A giant outburst is visible near the end of the light curve.

and 25-50 keV bands, which are summed and compared with Swift/BAT in Figure 3. Pulsations from H1417-624 are detected by the GBM pulsar monitoring technique [5].

XTE J1752-223, a new black hole transient discovered on October 23, 2009, with the *Rossi X-ray Timing Explorer (RXTE)* [6]. Figure 4 shows the GBM light curves in 5 energy bands, spanning 8-300 keV. This transient is one of seven sources detected with GBM above 100 keV [2]. XTE J1752-223 rose to a plateau in all bands from 12-300 keV for about 30 days. Then the source began brightening again. From examining the GBM light curves, this increase appears stronger in the 25-50 keV band than in the 12-25 keV range, suggesting possible spectral changes.

3.2. Persistent Sources

Sco X-1 is a bright Z-source. GBM detects it easily in less than a day in the 8-12, 12-25, and 25-50 keV

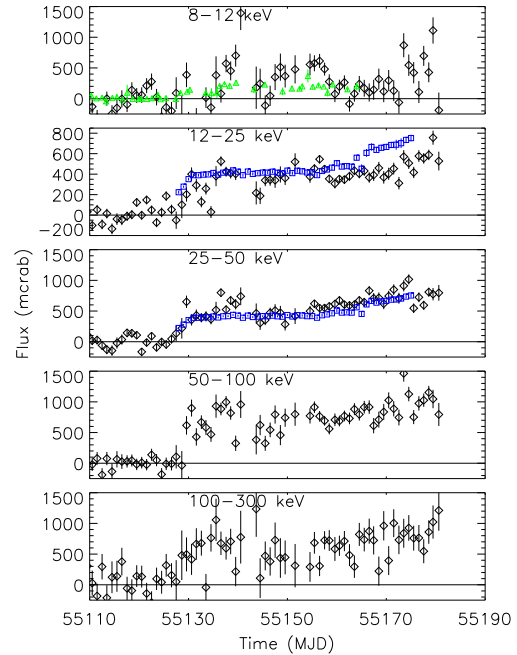


Figure 4: XTE J1752-223 outburst observed with GBM in 5 energy bands 8-12, 12-25, 25-50, 50-100, and 100-300 keV. RXTE/ASM 5-12 keV fluxes are overplotted for comparison in the 8-12 keV band. Swift/BAT 15-50 keV measurements are overplotted as blue squares for comparison to the GBM 12-25 and 25-50 keV bands.

bands. Sco X-1 is so bright that we have the potential to use single occultation steps for analysis. Figure 5 shows daily average fluxes.

GRS 1915+105 is a microquasar. GBM detects GRS 1915+105 on a daily basis in the 8-12, 12-25, and 25-50 keV, and 50-100 keV and on longer timescales in the 100-300 keV band [2]. Figure 6 shows three lower energy bands.

Cyg X-3 is a probable black-hole system. GBM detects Cyg X-3 on a daily basis in the 8-12, 12-25, and 25 to 50 keV bands. State changes are detected with GBM and agree well with Swift/BAT, as shown in Figure 7.

3.3. Extra-galactic Sources

Using the Earth occultation technique, we have monitored Cen A since August 2008. Cen A is detected on a daily basis in the 12-25 keV band and over longer timescales in the 25-50, 50-100, and 100-300 keV bands. See Figure 8 and Cherry et al. (2009) for more discussion. Two additional extra-galactic sources, Mrk 421 and 3C 454.3 have recently been added to the occultation catalog and monitoring is underway. As we iteratively improve our bright source list of X-ray binaries, we will be able to better investi-

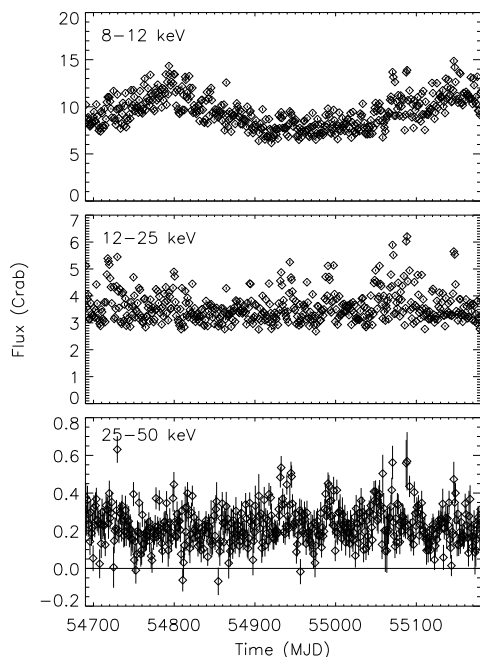


Figure 5: Sco X-1 GBM daily flux averages in the 8-12 (top), 12-25 (middle), and 25-50 keV (bottom) ranges.

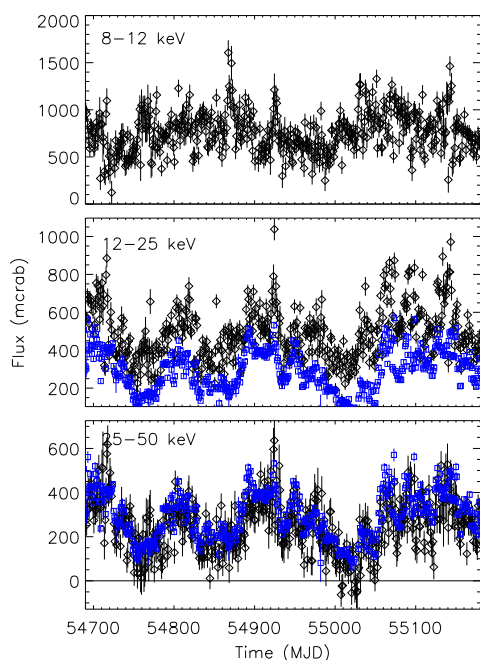


Figure 6: GRS 1915+105 GBM light curves in the 8-12 (top), 12-25 (middle), and 25-50 keV (bottom) bands. Higher energy light curves are shown in Cherry et al. (2009). Black diamonds denote GBM measurements and blue squares denote Swift/BAT 15-50 keV measurements.

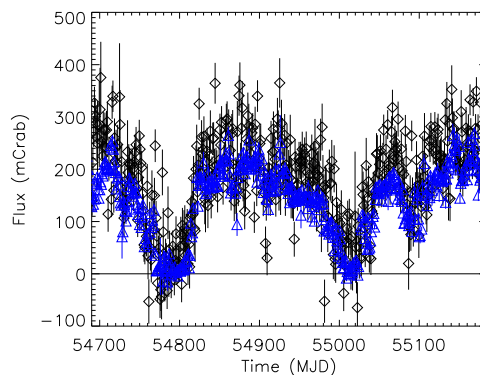


Figure 7: CYG X-3 GBM light curve in the 12-50 keV range. Black points are GBM 1-day averages. Blue points are Swift/BAT 15-50 keV measurements.

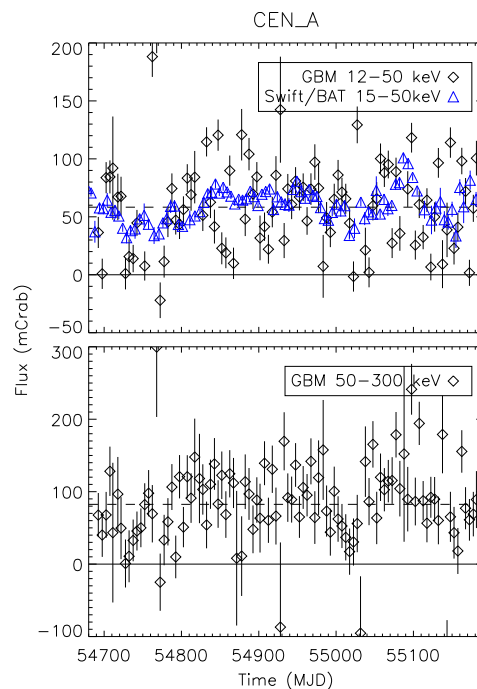


Figure 8: Cen A light curves in the 12-50 and 50-300 keV ranges. Black points denote GBM 5-day averages. Blue points denote 5-day average Swift/BAT 15-50 keV measurements. Dashed lines denote the average flux level in GBM.

gate fainter sources such as active galaxies and search for flaring activity.

4. Earth Occultation Monitoring Using the BGO Detectors

The Earth occultation technique can be applied to the higher energy BGO detectors on GBM, essentially

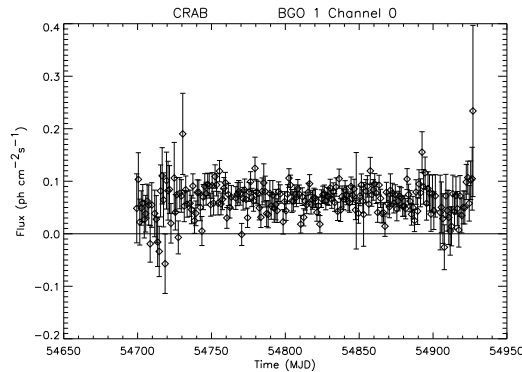


Figure 9: Daily average Earth occultation flux measurements for the Crab in BGO 1.

using identical software as for the NaI detectors. The BGO energy channel edges differ more significantly than the NaI edges, so fluxes are computed for the BGO detectors separately. The lower energy bounds of the CTIME channels are for BGO 0: 0.18, 0.34, 0.97, 2.1, 4.6, 9.8, 21, and 45 MeV and for BGO 1 are: 0.10, 0.38, 0.93, 2.1, 4.8, 10, 22, 46 MeV. In addition, many of the sources that are very bright that must be considered as interfering sources in the NaIs, e.g. Sco X-1, are not at all bright in the BGOs, so source interference must be addressed carefully as well. Code to monitor sources using the BGOs has just been developed. A light curve for the Crab is shown in Figure 9 for the 200-400 keV band in BGO 1, to demonstrate that preliminary runs have been successful.

5. SUMMARY

The GBM Earth occultation technique is working well. Agreement with Swift/BAT is good in the 15-50 keV range. Currently 64 sources are being monitored. Of these, we have preliminary detections for 42 sources in at least one of the energy bands between 8 keV and 300 keV. Future plans for the Earth occultation project include monitoring sources using the BGO detectors, expanding the catalog to include more extragalactic sources, and application of the technique to CSPEC data.

Acknowledgments

This paper uses quicklook results provided by the ASM/RXTE team and Swift/BAT transient monitor results provided by the Swift/BAT team.

References

- [1] E. Beklen & M.H. Finger, ATel #3276 (2009).
- [2] M. Cherry et al. these proceedings (2009).
- [3] B.A. Harmon et al. ApJS, 138, 149 (2002).
- [4] B.A. Harmon et al. ApJS, 154, 585 (2004).
- [5] M.H. Finger et al. these proceedings (2009).
- [6] C.B. Markwardt et al., ATel #2258 (2009).
- [7] C.A. Meegan et al., ApJ, 702, 791 (2009).
- [8] C.A. Wilson-Hodge, M.H. Finger, A. Camero-Arranz, V. Connaughton, ATel #2324, (2009).

Table I Monitored Sources as of December 14, 2009

Name	Right Ascension (deg)	Declination (deg)	Preliminary Detection
V0332+53	53.7500	53.1730	Y
CRAB	83.6330	22.0150	Y
A0535+262	84.7280	26.3160	Y
MXB0656-072	104.612	-7.26300	T
VELAX-1	135.529	-40.5550	Y
MRK421	166.114	38.2090	Y
GROJ1008-57	152.442	-58.2930	T
A1118-61	170.238	-61.9170	T
CENX-3	170.314	-60.6230	Y
1E1145.1-6141	176.869	-61.9537	
GX301-2	186.657	-62.7700	Y
GX304-1	195.321	-61.6018	
CEN A	201.365	-43.0190	Y
H1417-624	215.300	-62.7000	Y
CENX-4	224.592	-31.6690	
SWIFTJ1539.2-6227	234.818	-62.4590	T
H1608-522	243.175	-52.4170	
SCOX-1	244.980	-15.6400	Y
IGRJ16318-4848	247.967	-48.8030	Y
AXJ1631.9-4752	248.008	-47.8740	Y
4U1636-536	250.231	-53.7510	Y
GX340+0	251.449	-45.6111	Y
HERX-1	254.457	35.3420	Y
OA01657-415	255.199	-41.6730	Y
GX339-4	255.706	-48.7890	
4U1700-377	255.986	-37.8440	Y
GX349+2	256.450	-36.4170	Y
4U1702-429	256.564	-43.0361	Y
H1705-440	257.228	-44.1010	Y
GX354-0	263.000	-33.8330	Y
GX1+4	263.008	-24.7470	Y
1E1740-29	265.969	-29.7420	Y
1A1742-294	266.523	-29.5150	Y
IGRJ17464-3213	266.575	-32.2400	Y
IGRJ17473-2721	266.825	-27.3440	Y
XTEJ1752-223	268.044	-22.3250	Y
SWIFTJ1753.5-0127	268.368	-1.45300	Y
GX5-1	270.275	-25.0830	Y
GX17+2	274.006	-14.0360	Y
H1820-303	275.925	-30.3670	Y
SWIFTJ1842.5-1124	280.500	-11.4000	
GS1843+00	281.412	0.891000	Y
AQLX-1	287.817	0.584900	
GRS1915+105	288.820	10.9700	Y
CYGX-1	299.590	35.2020	Y
EXO2030+375	308.064	37.6390	Y
CYGX-3	308.107	40.9580	Y
GINGA2138+56	324.878	56.9861	T
CYGX-2	326.170	38.3200	Y

Table II Recently Added Sources

Name	R.A. (deg)	Decl. (deg)
LSI+61 303	40.1319	61.2293
4U1538-52	235.597	-52.3860
X1624-490	247.011	-49.1983
4U1626-67	248.070	-67.4620
SWIFTJ1713.4-4219	258.361	-42.3270
GX9+9	262.934	-16.9614
X1735-444	264.743	-44.4500
GX3+1	266.984	-26.5636
GX9+1	270.382	-20.5310
GX13+1	273.632	-17.1559
GS1826-238	277.367	-23.7970
SERX-1	279.990	5.03560
HT1900.1-2455	285.036	-24.9205
4U1954+31	298.929	32.1000
3C454.3	343.490	16.1480

All-Sky Earth Occultation Observations with the Fermi Gamma Ray Burst Monitor

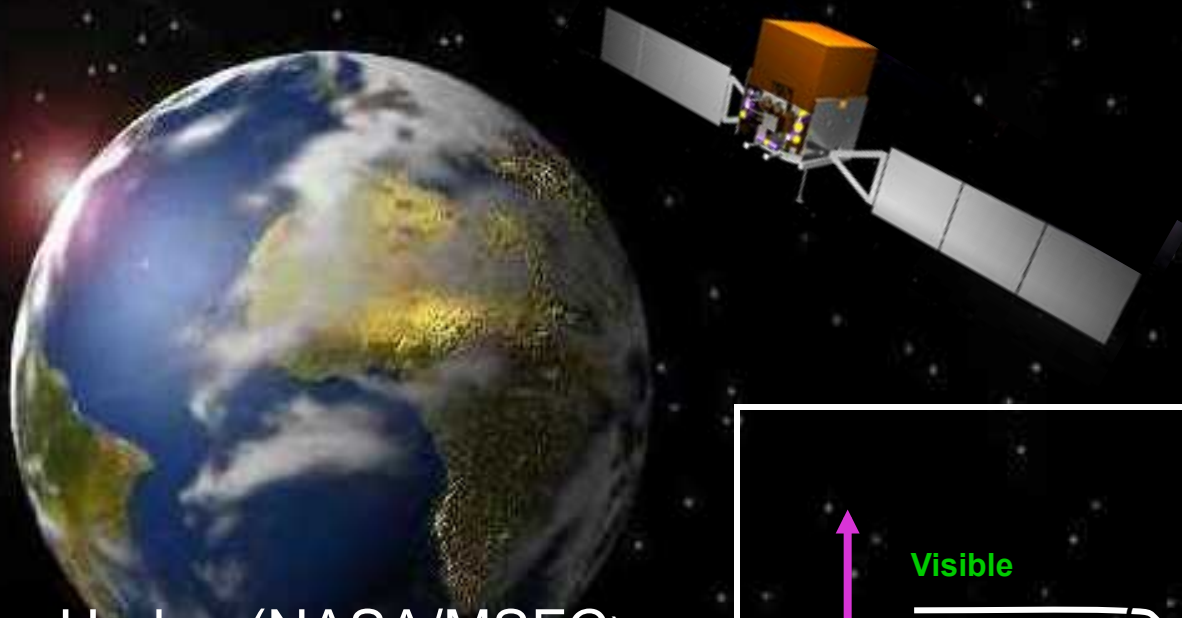
C.A. Wilson-Hodge, E. Beklen, P.N. Bhat, M. Briggs, A. Camero-Arranz, G. Case, V. Chaplin, M. Cherry, V. Connaughton, M. Finger, R.H. Haynes, R. Preece, J. Rodi, for the GBM Earth Occultation Team

Using the Gamma Ray Burst Monitor (GBM) on-board Fermi, we are monitoring the hard X-ray/soft gamma ray sky using the Earth occultation technique.

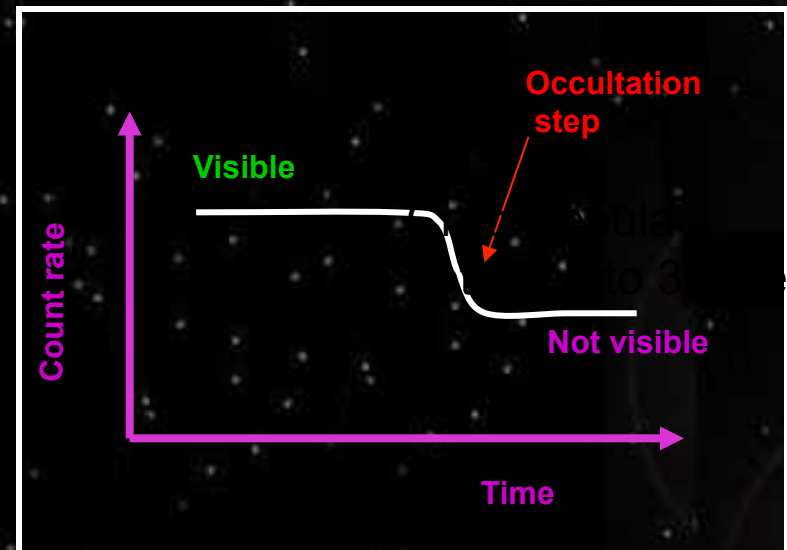
Each time a source in our catalog is occulted by (or exits occultation by) the Earth, we measure its flux using the change in count rates due to the occultation. Currently we are using CTIME data with 8 energy channels spanning 8 keV to 1 MeV for the GBM NaI detectors and spanning 150 keV to 40 MeV for the GBM BGO detectors. Our preliminary catalog consists of galactic X-ray binaries, the Crab Nebula, and active galactic nuclei. In addition, to Earth occultations, we have observed numerous occultations with Fermi's solar panels. We will present early results.

Regularly updated results can be found on our website
<http://gammaray.nsstc.nasa.gov/gbm/science/occultation>.

All-Sky Earth Occultation Observations with the Fermi Gamma-ray Burst Monitor

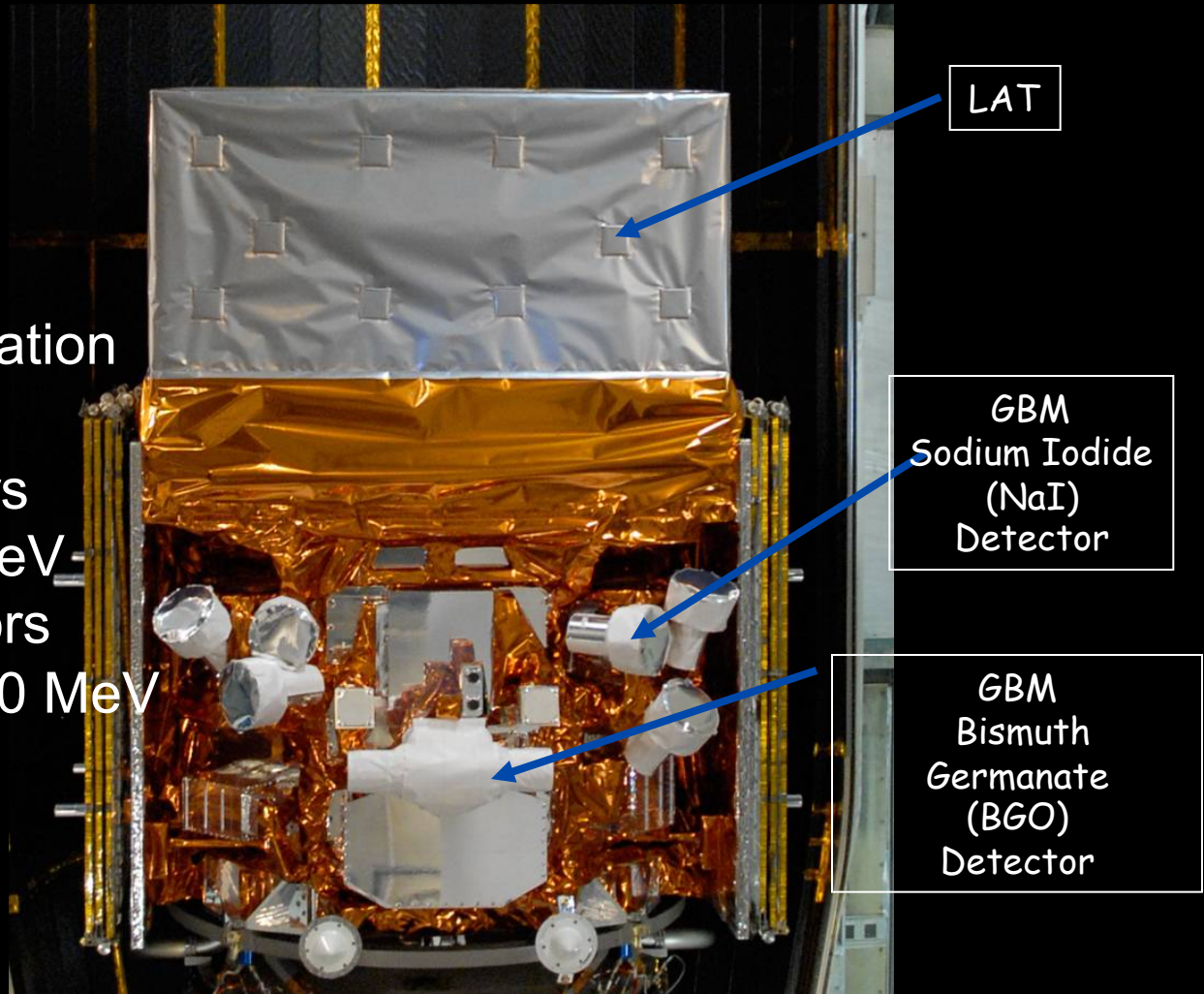


C.A. Wilson-Hodge (NASA/MSFC),
G. Case, M. Cherry, J. Rodi (LSU), M.
Finger, P. Jenke (USRA), A. Camero-Arranz
(NSSTC), V. Chaplin, V. Connaughton, P.N.
Bhat, M. Briggs (UAH), E. Beklen (METU),
R.H. Haynes (NASA Academy) for the GBM
Earth Occultation Team



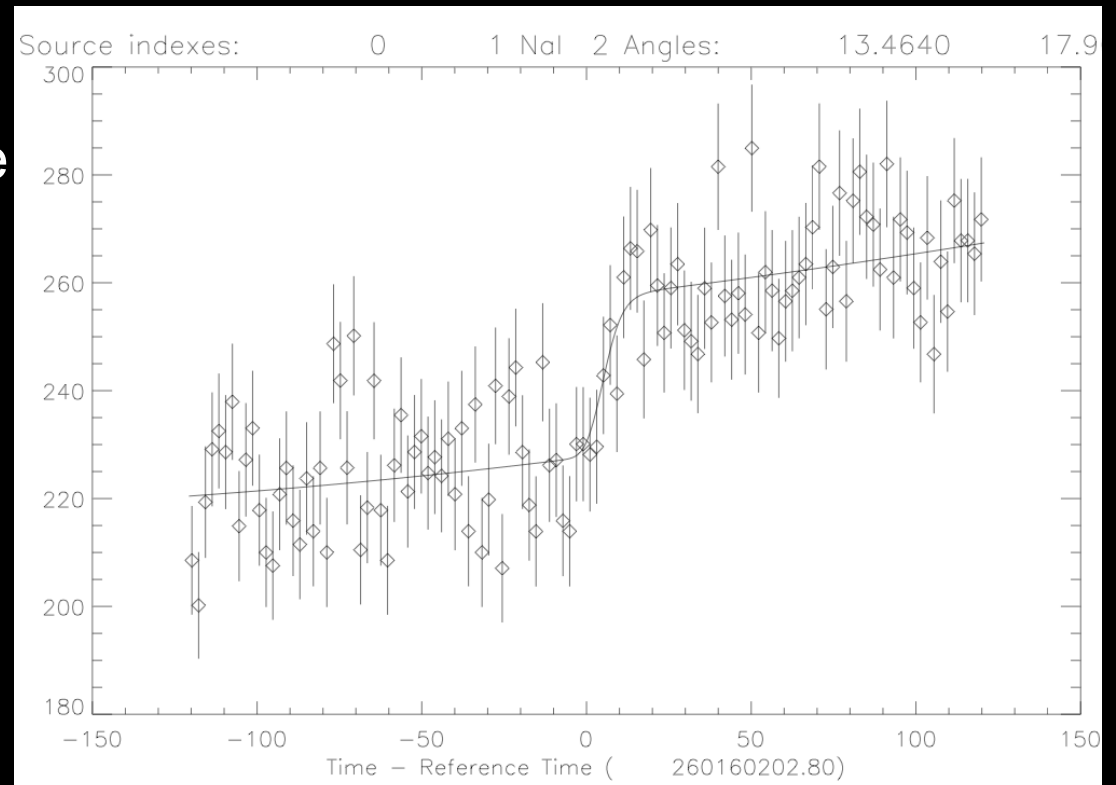
Fermi GBM

- Fermi
 - 565 km orbit
 - 26.5 deg inclination
- GBM
 - 12 NaI detectors
 - 8keV - 1 MeV
 - 2 BGO detectors
 - 150 keV - 40 MeV



Earth Occultation Step Fitting

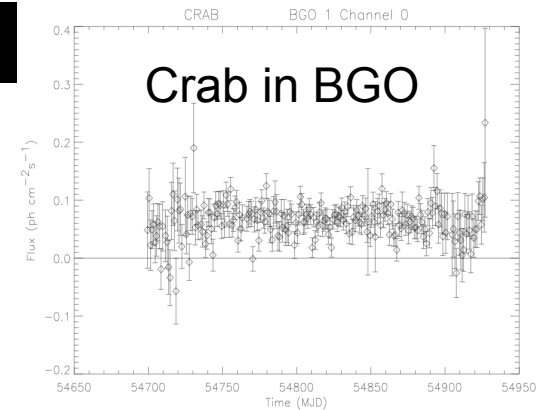
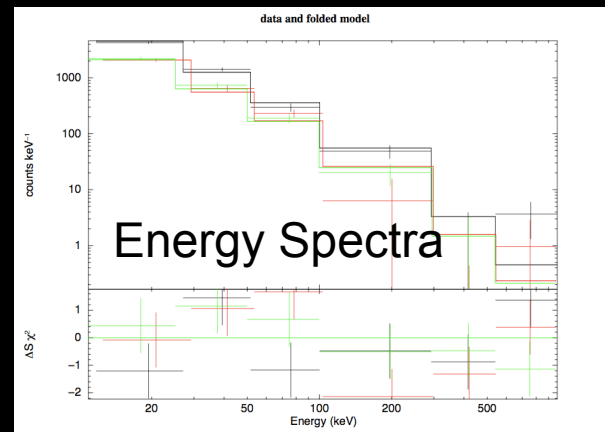
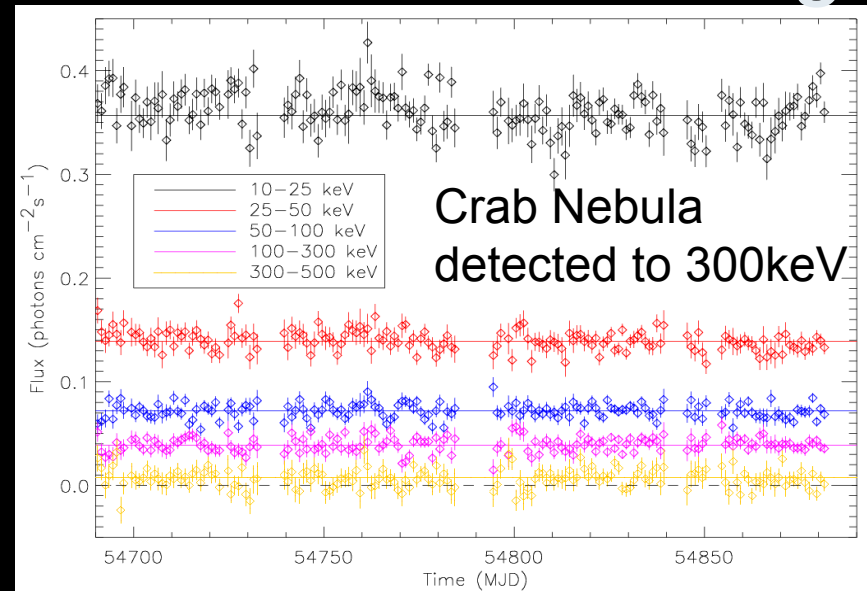
- Occultation times
- Detectors viewing source of interest
- Blockages?
- Fit to each detector and channel
 - Background model
 - Model count rates
 - Detector responses
 - Assumed energy spectrum
 - Atmospheric transmission
- Compute best scale factor for all detectors to estimate fluxes.



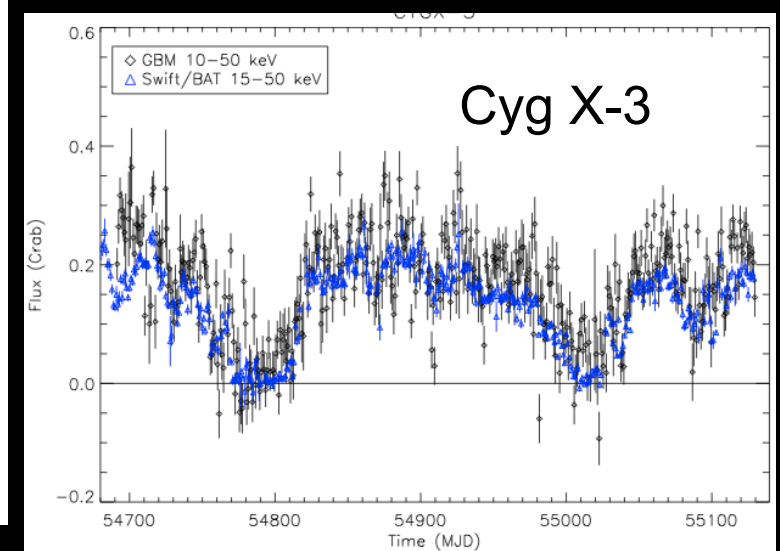
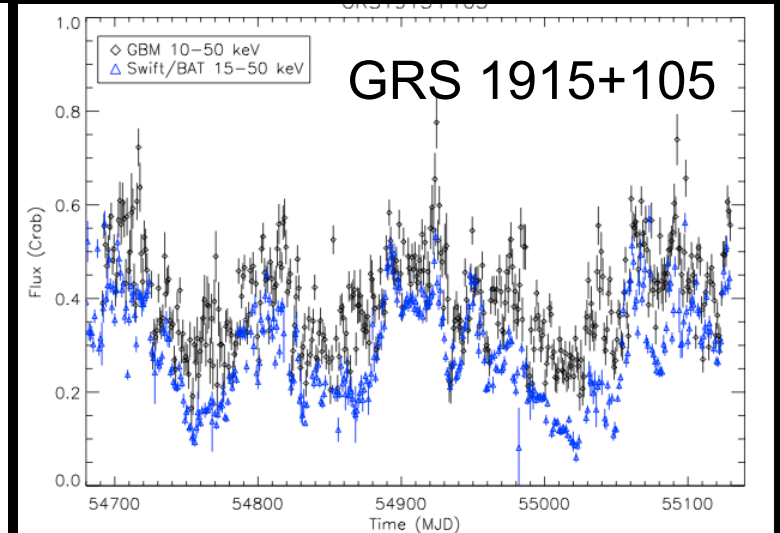
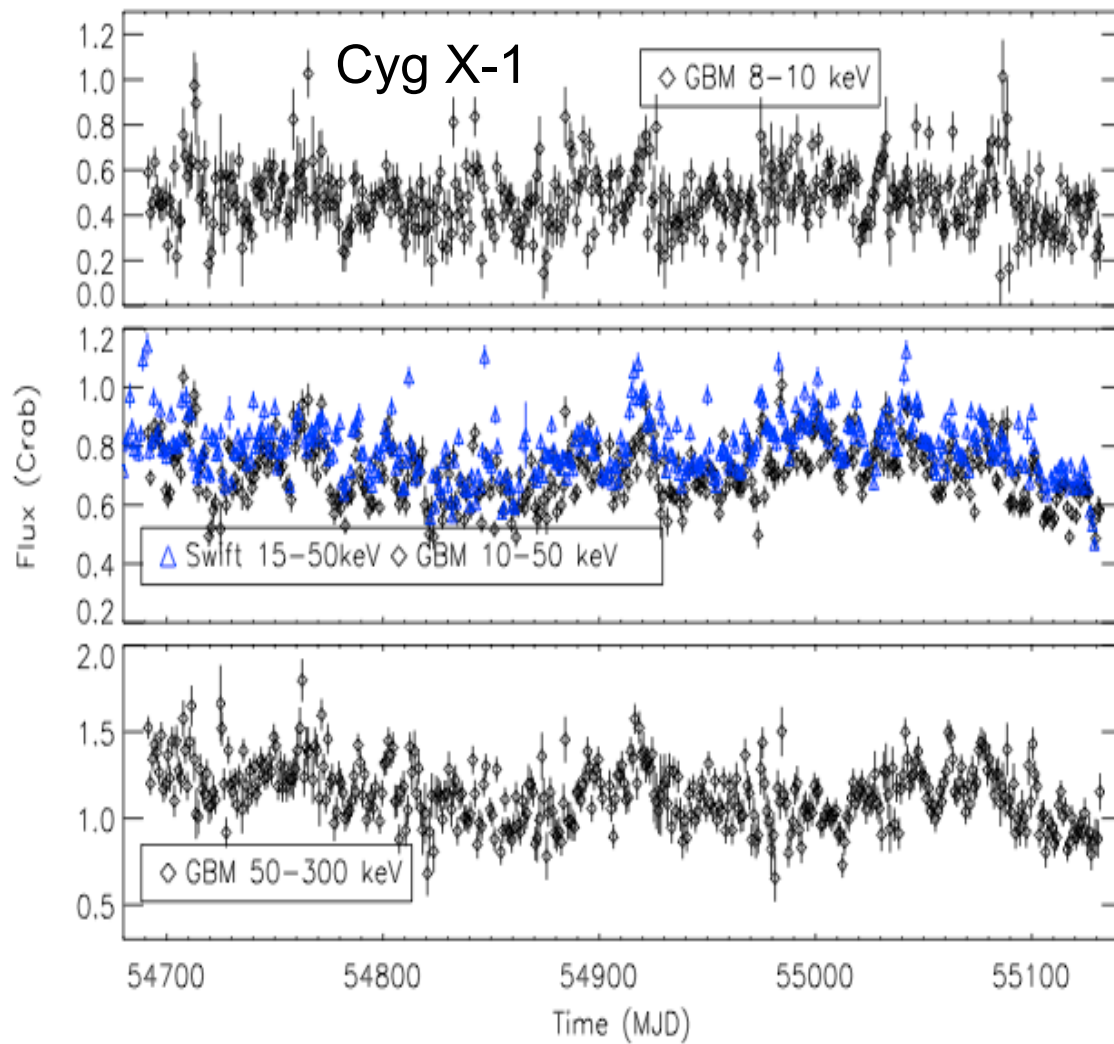
- Fermi/CGRO differences
 - Fermi rocks to +/-35 deg from Zenith every orbit
 - Detector blockages

GBM Earth occultation monitoring

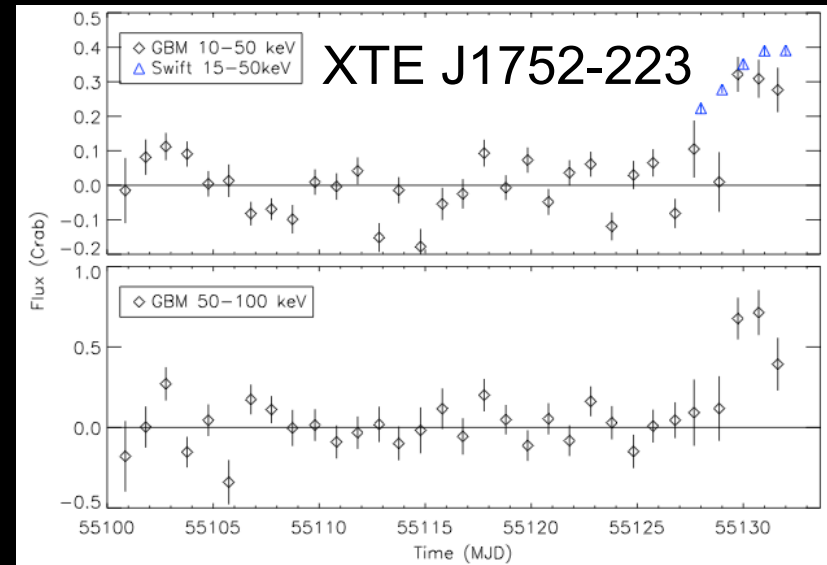
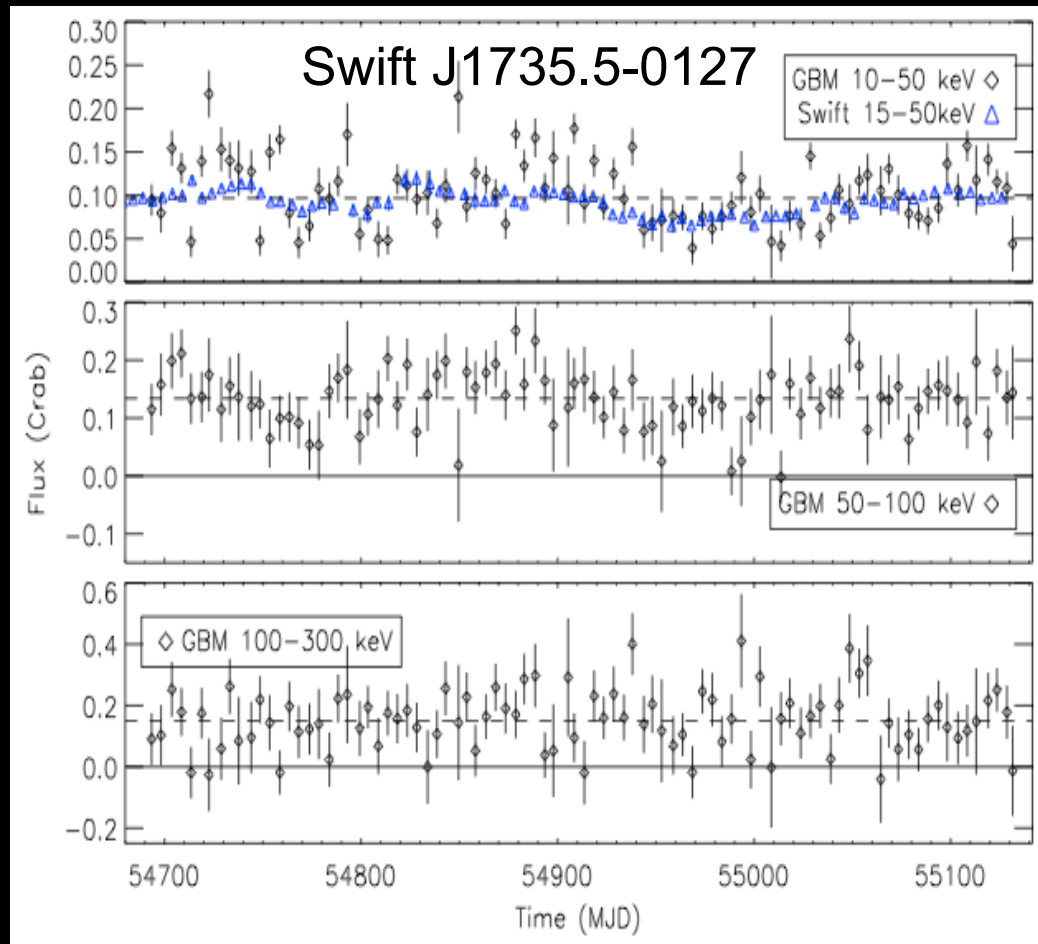
- Initial catalog of 45 sources
 - X-ray binaries
 - Crab
 - Cen A
- Many sources will be added to catalog
- CTIME data (8 channel, 256 ms time resolution)
- Fit a 4 minute window around each step
- Include bright sources occulting in window
- Optimizing bright source inclusion



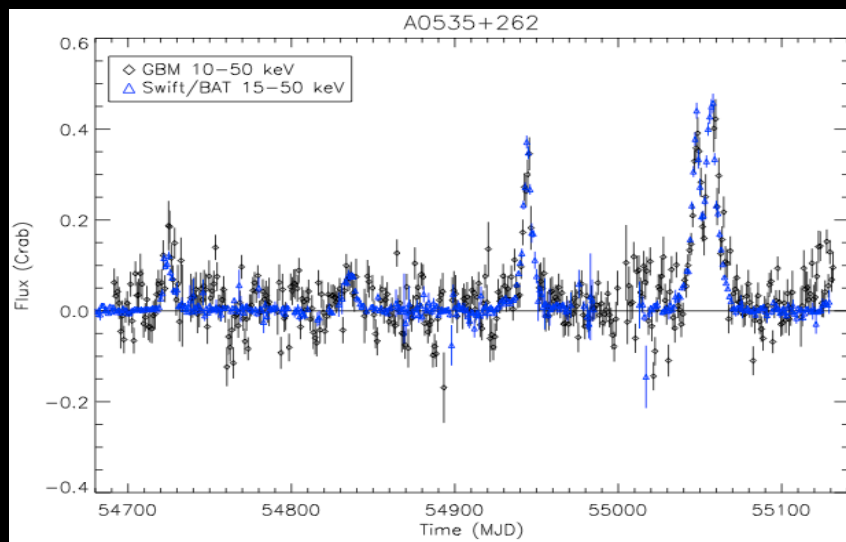
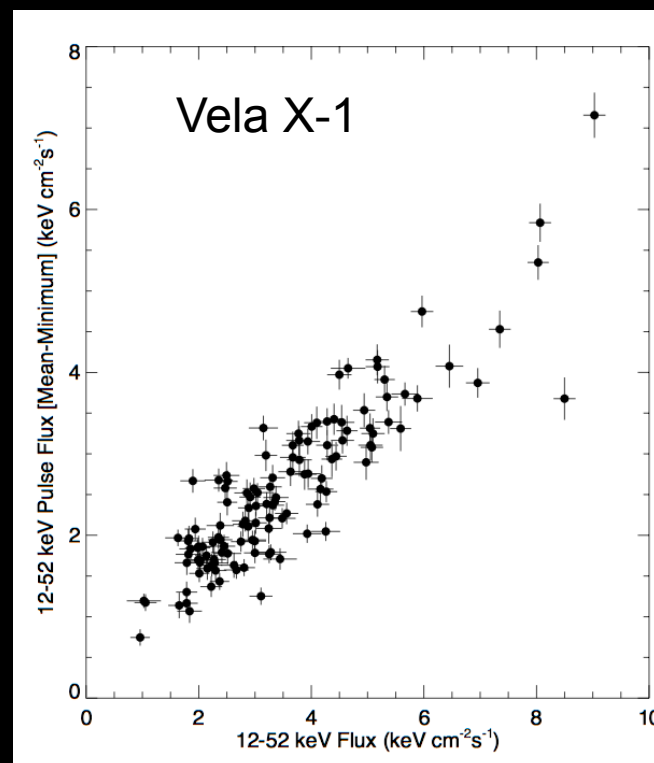
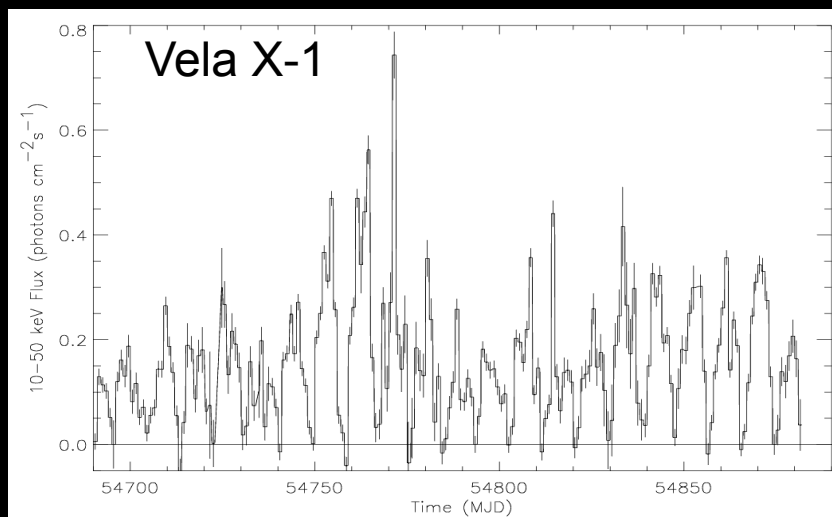
Black Hole Binaries with GBM and Swift/BAT



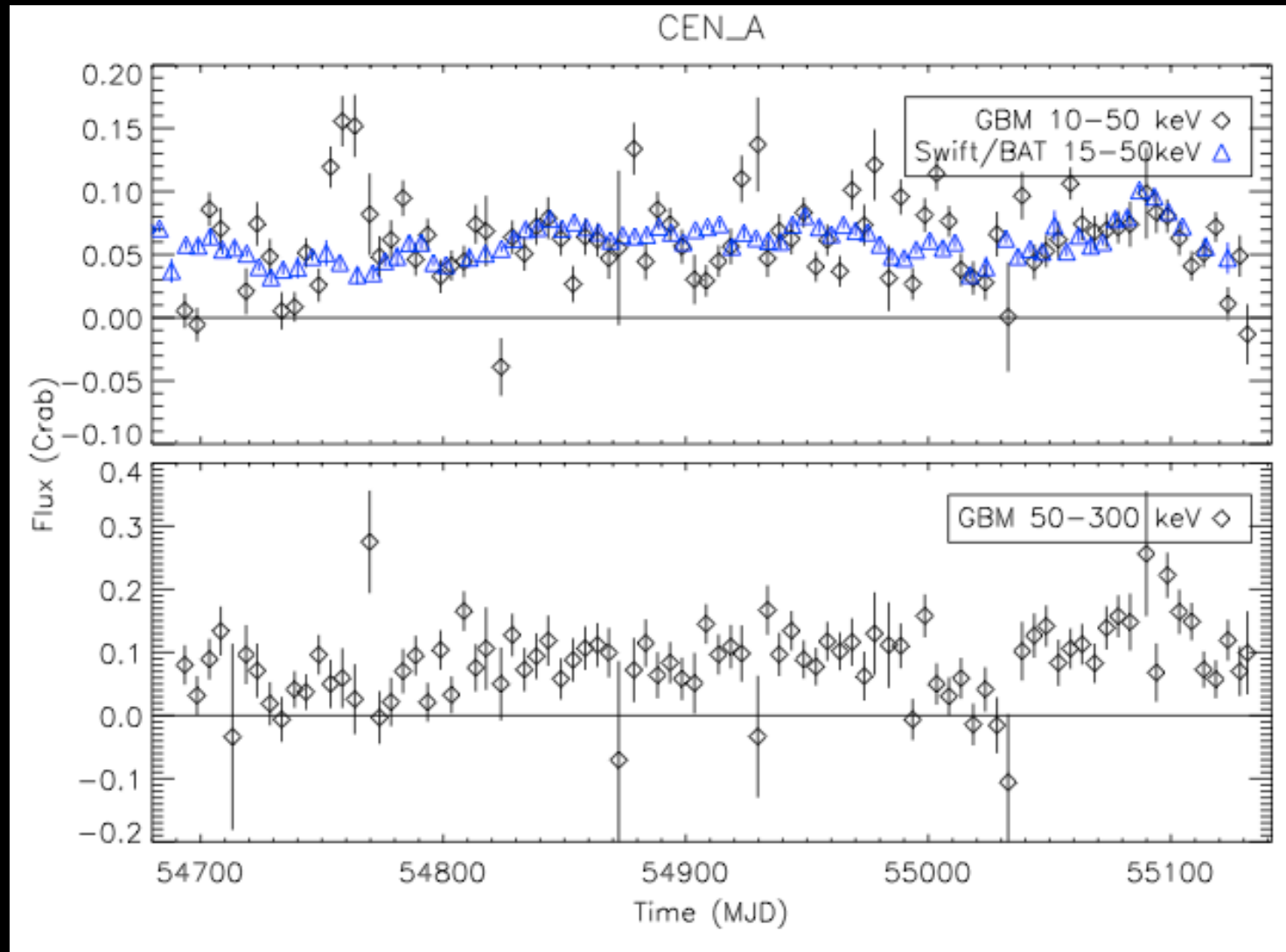
More Black Hole Binaries



Accreting Pulsars with GBM Earth Occultation



AGNs with GBM Earth Occultation



Summary

- GBM Earth occultation technique is working nicely
- Source monitoring is underway
- Agreement with Swift/BAT is good
- Detections in the 100-300 keV band
- Watch our website for new light curves
- <http://gammaray.nsstc.nasa.gov/gbm/science/occultation/>